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A COMMON FRAMEWORK FOR INTEGRATING THE ECONOMIC AND ECOLOGIC DIMENSIONS OF HUMAN ECOSYSTEMS. I: GENERAL CONSIDERATIONS

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PREFACE

The interactions between agriculture and the environment have emerged as important factors linking the concerns of the agriculturist, the economist, the ecologist, and the systems analyst. Recognition of their importance has led to the establishment of a task at IIASA to study the environmental problems of agriculture. This task will look at environmental problems at the field level and at the regional and national levels, and it will attempt to provide a framework which can allow insights made at one level to become meaningful at the other as well.

This paper is the first in a series outlining a methodology for looking at agriculture and environment in a single context. This methodology will be applied to the task and should prove as one mechanism for expediting cooperation and collaboration between different parts of the joint effort.

ABSTRACT

Human ecosystems such as agriculture can be viewed as multi-stratum hierarchical systems with control being exerted by various sectors of society, impinging on the modified environment, and guided by overall societal goals. Many potential controlling inputs are available, but the system as a whole is not fully controllable. Most analyses of human ecosystems have adopted this approach implicitly. But they tend to concentrate on only one stratum, so that there is little communication between analysts concerned with different levels or the models they espouse. There are many valid reasons for this lack of communication for certain sorts of analyses, but there are also many emerging problems which require a more comprehensive approach in which different strata are coupled. The views of the system characterizing different levels must be made mutually compatible, and information must be able to flow throughout the key parts of the system. These criteria impose requirements for time resolution and the character of each variable involved in the communication linkage. But if these requirements are met, the construction of substantial multi-stratum models of human ecosystems can be carried out and validated.

A Common Framework for Integrating the Economic and Ecologic Dimensions of Human Ecosystems. I: General Consideration

Human ecosystems (Clapham, 1976, Pestel and Gottwald, 1974) represent a class of extremely complex systems which must be treated in different ways for different purposes of analysis. For some investigators, the rules governing the human ecosystems are economic; the problem is to understand the process by which decisions are made about the use of available technical, chemical, or labor resources for production of agricultural commodities, timber, fish, and so forth. Others concentrate on the geographic distribution of management types and the associated patterns of land use and exploitation of biological resources; the problem is the appropriateness of these patterns to the basic characteristics of the environment. For still others, human ecosystems comprise the interactions between animals, plants, soil, water and the associated cycles of nutrients, water, and population. Of course, any human ecosystem is all of these. The observer may choose which focus he wishes to have. This focus commonly corresponds to a disciplinary view of the system. Such views generally have considerable power, and many useful insights can be gained from them.

But increasingly often, the disciplinary views are not sufficient to deal with newly perceived problems. Let us consider agriculture as an example of a particularly important human ecosystem. It can be seen as a set of processes requiring decisions regarding the use of inputs to gain outputs. But these processes do not exist in a vacuum. Furthermore, the physical-biological-chemical environment that forms the context for these processes is not static, but rather volatile and dynamic. Likewise, the plant-soil-water system of a given farmer's field exists in the context of a set of decision-making structures that determine the addition of all types of inputs to that system.

This paper is devoted to those problems of agriculture for which one must consider both the decision-making behavior of the system (here termed collectively the "economic" activities) and the biological-chemical-physical aspects of the system (here termed the "ecologic" activities) in the same analysis. Both are part of the same system and many problems are handled effectively by system decompositions other than the usual or classical disciplinary breakdowns. But it is very difficult to combine the ecological and economic viewpoints in a single analysis. Not only is there an inertia to disciplinary boundaries, there are also system-given reasons why cross-disciplinary linkages of this sort are difficult to establish. But one can create a common framework within which the economic and ecologic behavior of a human ecosystem such as agriculture can be examined.

At its most basic, an agricultural system comprises biological populations, soil, water and other natural or quasi-natural factors which interact according to well-established biological and ecological laws. Society acts consciously to control these subsystems by imposing certain actions on them, and the specific structure of the system and the constraints acting on it are due largely to the nature of the dominant social system. These control functions rest with the social system. But the system as a whole is not fully controllable. There are many factors which cannot be altered directly by the society, and indeed there are many which cannot even be observed.

AGRICULTURAL SYSTEMS AS MULTILEVEL HIERARCHICAL SYSTEMS

A meaningful approach to study the linkages of different subsystems within an agricultural system is the multilevel hierarchical decomposition as developed by Mesarović and his associates (Mesarović and Macko, 1969, Mesarović *et al.*, 1970). That is, the overall system can be decomposed into several subsystems, each of which has its own properties. These subsystems are then arrayed into several strata, each of which has characteristics of its own. Subsystems are linked by system-wide information flow. But the decomposition of the system into strata implies that there is direct interaction only between neighboring strata and that there is a notable asymmetry to information flow across strata. In general, information from higher to lower strata is control information, while information flow from lower to higher strata is process information.

As an example of a multi-stratum hierarchical system, consider a factory manufacturing farm machinery (Figure 1). It can be viewed as a 3-level system. The lowest comprises the processes involved with actual fabrication of the products. The middle level is concerned not with direct production but rather with determining demand for the products, sources of supply for raw materials and allocation of specific resources and personnel throughout the factory. The highest level is concerned with overall coordination of the plant. Each level depends on information from subsystems above and below it in the hierarchy, and the controlling roles of the higher strata are quite clear. The functions of each sector and each level in the system are different, and yet all are essential for satisfactory functioning of the total system.

An important feature of the multilevel hierarchical system concept is that any subsystem of one stratum in the hierarchy can be represented as a much more aggregate element of another stratum in the hierarchy. For example, on the fabrication stratum of the factory, a foundry may be viewed as a very complex system of people, products and processes. However, if the foundry is viewed from the middle management level, it can be represented as a "black box" labeled "foundry" which needs certain raw materials as inputs and which yields certain products as outputs. While the middle manager may need to know how the foundry operates and may in fact be very highly involved with certain aspects of its operation, the organization of the middle management level requires only that the existence of the foundry and basic interactions between the foundry and the higher level be considered. Likewise, the highest level of management need

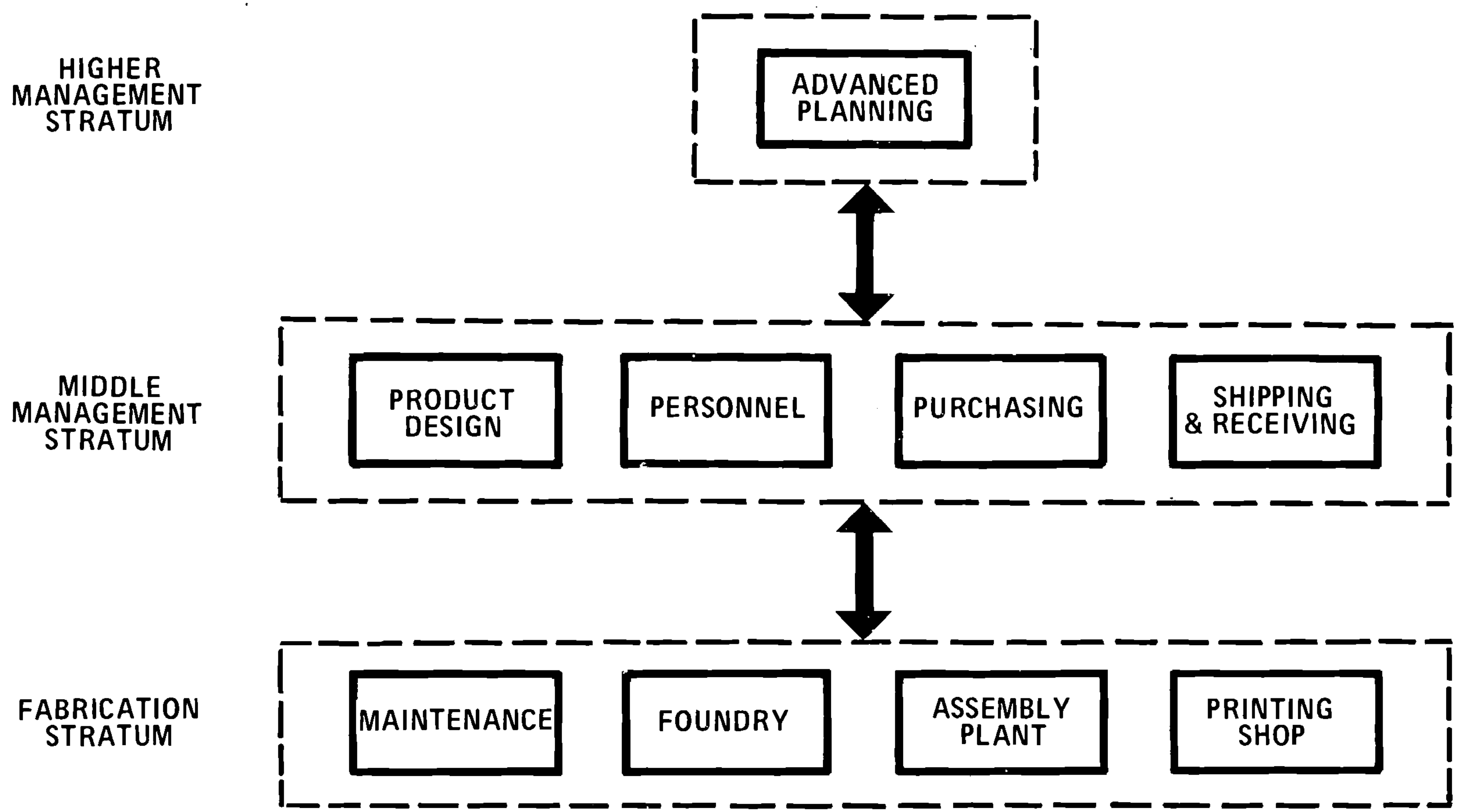

Figure 1. Subsystems included in a factory manufacturing farm machinery, arrayed in a 3-stratum hierarchical system. All units within a stratum are assumed to affect each other.

not concern itself with the day-to-day operations of either the middle management level or of the fabrication level. From the highest level, each sector at the middle management level can be viewed as a black box representing a certain set of coordination tools. Highest level management may, in fact, be intimately aware of the way in which sectors at lower strata carry out their functions, but what is important for the organization of the system is *that* the functions are carried out in accordance with overall objectives, not *how* they are carried out.

An agricultural system can be represented as a multi-stratum hierarchical system as shown in Figure 2. On the lowest, or "natural" stratum are those elements with which we generally associate field-level phenomena. These include the interactions between species, crop and livestock responses to various inputs, soil water and nutrient balances, and the interacting dynamics of animals, plants, soil, water, and nutrients. The basic principles underlying the behavior of the subsystems on this stratum are entirely independent of management even though overall system state at any point in time is conditioned by human intervention. As an example, the laws governing the nutrient responses of a crop with a given genetic composition are completely unrelated to whether or not fertilizer is spread on the field. But the productivity of the crop stand are affected by whether or not a farmer fertilizers his field, since fertilization alters the field's nutrient status. In the same way, the responses of the crop population to a pest attack of a given intensity are independent of any technical intervention of which man is capable. He can, of course, introduce a chemical pesticide into the system to lower the intensity of the pest attack. This may reduce crop losses. But the mechanism for this reduction is the response of the pest to the pesticide. This response is governed by genetic characteristics of the pest population and is an intrinsic feature not easily manipulated by man (although Whitten *et al.* (1971), among others, suggest ways of genetic manipulation for pest control; these are still in very early stages of development). This response may also be affected by crop fertilization,

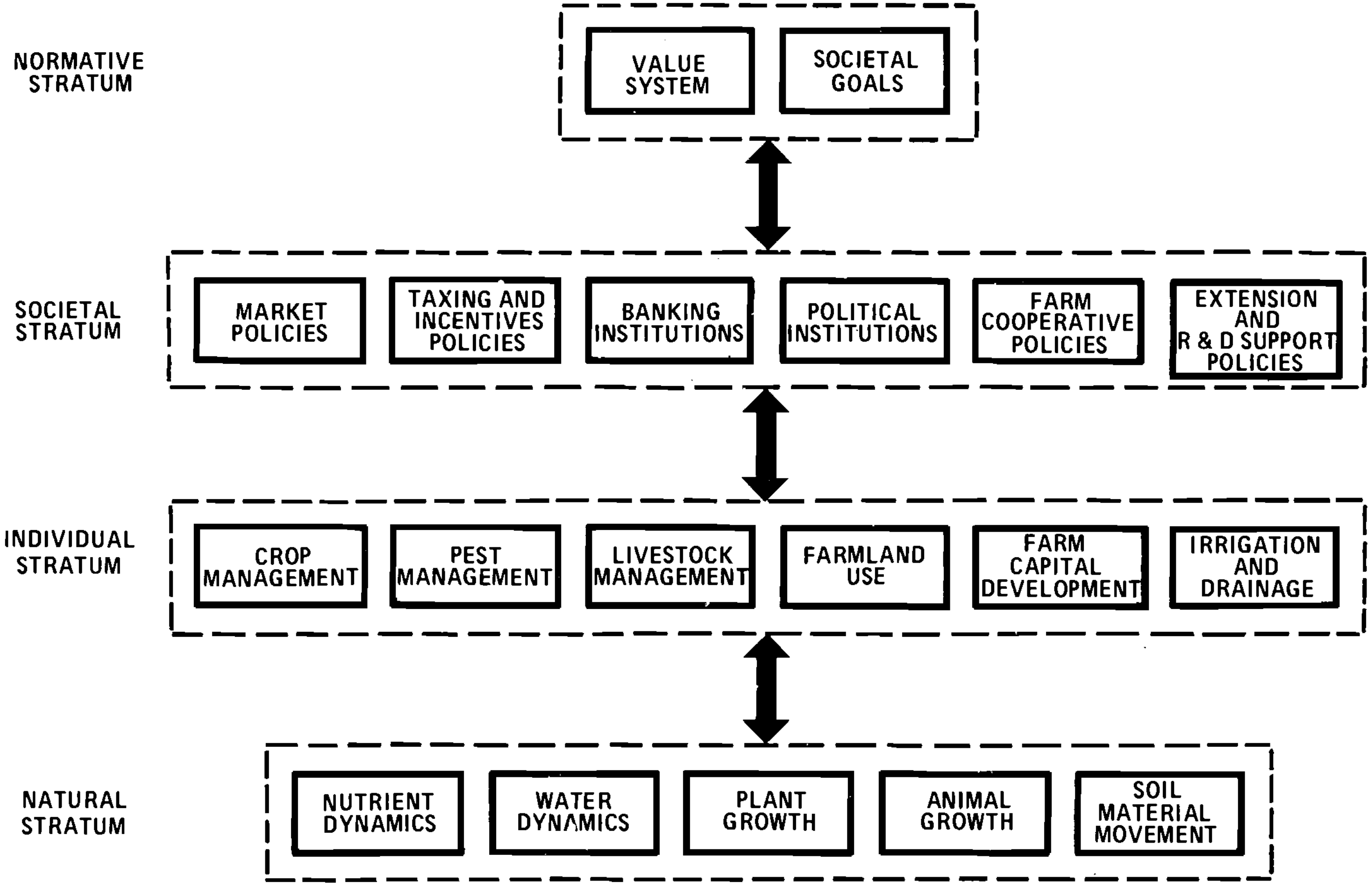

Figure 2. Agriculture as a multilevel hierarchical system. Note that only those parts of the society directly involved with agriculture are shown. On the decision-making strata, there are also other actors who may also attempt to influence the natural stratum or who monitor its state. They may cause adaptation in the societal decision-making and normative strata, and their indirect impact on agriculture may be substantial. All processes or phenomena within a stratum are assumed to affect each other.

but this is due to the increase in biomass of the crop population that generally follows fertilization rather than any direct influence of man. We can consider the energy and materials flow throughout the community and between the abiotic and biotic sectors of the system as the communication system which unifies the natural stratum within the context of the larger agricultural system.

The middle strata of the system comprise those portions of the social system which we most commonly associate with management. Here are the political, economic, organizational, and technological portions of the society. As with the middle-management stratum of the factory, they can be regarded as locating and allocating resources within the system as a whole. Unlike the factory, however, it makes sense to recognize the very different roles of management on a lower or "individual" level whereon the decisions of individual farmers and managers are made and on a higher "societal" level reflecting the institutional behavior of the society. The concerns of the latter are much broader than the former, and the fundamental instruments at its disposal are generally much more powerful. Nevertheless, the impact of the farmer on the natural stratum is more direct, and any attempt to understand the actual configuration of a human ecosystem must consider decision-making on both levels. Finally, at the highest stratum lies the normative structure of the society, including its value structure, goals and so forth.

The four strata together comprise the total agricultural system. Regardless of the subset of this sytem we would wish to consider for any given analysis, and regardless of the decomposition we prefer, it is nevertheless true that the system always functions in the real world as an entity.

It is implicit in the multilevel view that the interconnections between strata are sparser and generally looser than those within a stratum. There is both a practical and a theoretical reason for this. From a practical viewpoint, it would not be useful to create a hierarchy in which interconnections across stratum boundaries were very close. Indeed this is precluded by the notion that a subsystem on one stratum can be viewed as a more aggregate subsystem on an adjacent level. From a theoretical viewpoint, the asymmetry of information flow requires that there be a difference in time horizon and time resolution on different strata. Information crossing strata downward is control information, while the information crossing upward is process information. Processes generally operate on higher time resolution than control. This is so because control must wait for a response. Furthermore, at least in a system such as agriculture, a change in control strategy requires that controllers, (in this case society and the farmer) be able to perceive a set of trajectories for the processes they wish to control. Once a trajectory is established, they can then respond by changing their strategy in an effort to alter it.

This is a standard pattern of control-reaction-monitor-adaptation shown diagrammatically in Figure 3. It is most effective when the reaction time is short relative to the adaptation time, so that the effectiveness of adaptation can be gauged. But environmental problems are often characterized by considerable inertia, so that the response of the system to a single control input may continue for long periods of time. It is virtually never clear how much the observed trajectory of any such phenomenon depends on the inertia of the system as opposed to adaptive control (Clapham and Pestel, 1978b). This is often compounded by the fact that such phenomena may be important in the long term as well as in the short-run and that adaptation may be directed only to the short-term behavior of the system. The result is that the momentum of the system over the long term becomes too powerful for the controller, and it assumes a state from which further control is impossible or at least impracticable. Examples of such irreversible change include eutrophication and desertification.

In complex systems analysis, most approaches can be viewed as being guided by hierarchical decomposition into strata. However, this decomposition principle is commonly used unconsciously,

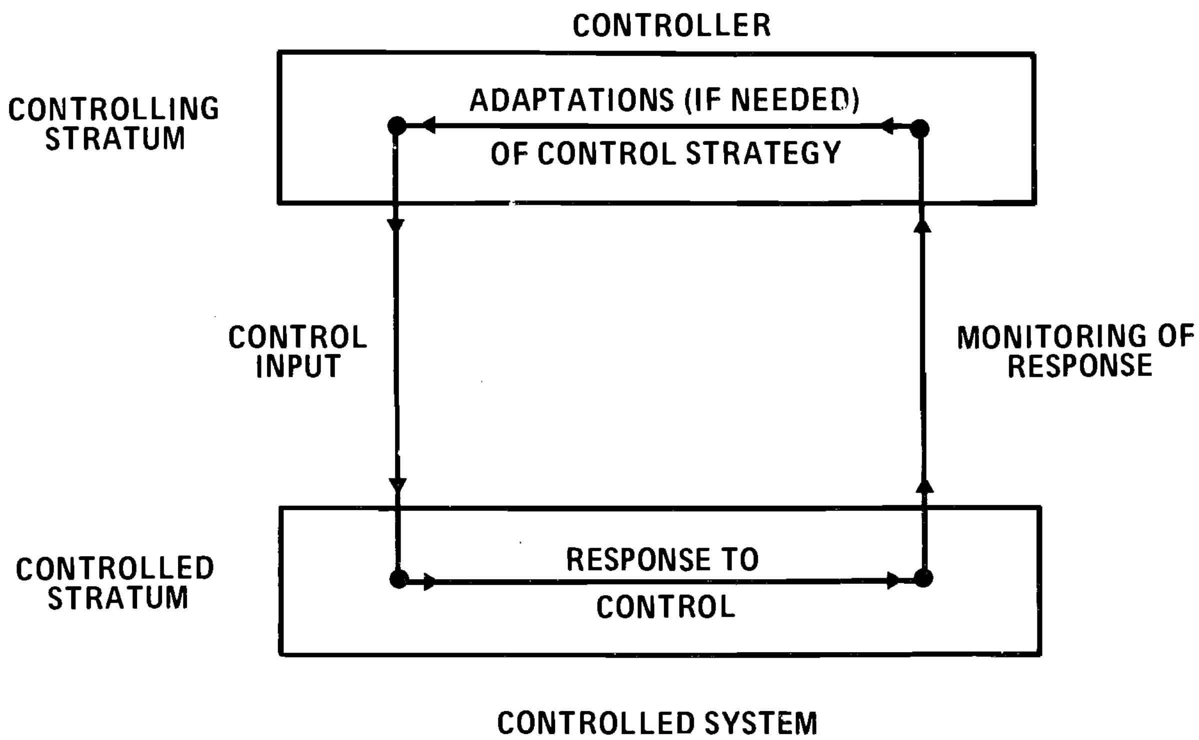

Figure 3. Interactions between controlling and controlled systems.

so that the analytical power of the multilevel hierarchical system notion is not used. A single stratum is taken as the primary focus. Control information passing from higher strata is taken as exogenous or constant; process information from lower strata is considered either as constant or as embodied in parameter estimation procedures. These assumptions are reasonable for systems whose strata are not coupled through strong feedbacks, within the time horizon of the analysis. This property, which might be called "interstratal equilibrium", is characteristic of agricultural systems whose techniques have remained relatively constant over a fairly long time. But modern agriculture is in such a fluid state that the system may be far from interstratal equilibrium, so that the strict decomposition between strata can lead to insufficient or mistaken analysis.

The characteristics of the subsystems featured in an analysis often carry over to the analysis itself. For example, if one is concerned mainly with the economic decision-making processes within the agricultural system, then one tends to adopt a mind-view that includes a moderate time frame (generally on the order of about a year or so and rarely more than five) and a primary focus on the institutional or the farmer level. This view does not worry too much about details of the natural stratum and will often concentrate on one decision-making stratum to the exclusion of the other. Conversely, if one adopts a soils view, one is concerned with much shorter-range phenomena (with a resolution of a few days) or with very long processes which evolve over several years (at least a few and perhaps up to 100 or more)--or perhaps with both. At the same time, one will not worry too much about the decision processes by which inputs are determined; the important processes are those which occur after the inputs have been made.

The economist (to label the practitioner of the higher-stratum view), is likely to view the natural scientist (to label the practitioner of the lower-stratum view) as one who is more concerned with the details of the sex life of animals and plants or of arcane aspects of soil chemistry and physics than he is with the real world of finance and policy. The natural scientist, on the other hand, may look upon the economist as a practitioner in black magic whose models are totally empirical and bear no relation to any of the well established principles upon which real processes operate in the real world. Nevertheless, both viewpoints are directed toward the same system, and the differences between them are artifacts of the stratal decomposition. Both views are sufficient when strong decomposition is warranted. But neither is sufficient for a system in which significant feedbacks across stratum boundaries must be considered.

Feedbacks and Coupling of Information Flows Across Strata

It is not always clear *a priori* how detailed the consideration of cross-stratum coupling need be for realistic problem assessment of a given human ecosystem. The importance of the coupling is related to the intensity of feedback between strata. Control input from a higher stratum may alter the structure of the lower stratum so that it returns feedback information to which the higher stratum must respond within its usual time scale. This is often true for human ecosystems in general. But cross-stratum feedbacks may also be much weaker; this assumption is usually made for modeling in applied ecology.

We can consider two kinds of human ecosystems, which can be named exploitation and pollution ecosystems (Clapham, 1976). In the exploitation ecosystem, the information traveling up the hierarchy from the natural stratum to the social strata concerns essential raw materials for the operation of the social strata. Agricultural systems are typical examples. The economic, political, and marketing structures which lie at the intermediate level all depend on the flow of foodstuffs to some degree for their own operation. The control information which travels down the hierarchy into the natural stratum is designed to manage the natural stratum so that the flow of foodstuffs (or whatever other materials) is maintained at the desired level.

In a pollution ecosystem, on the other hand, the flow of information from the natural stratum to the social strata does not relate to basic raw materials. There is no material feedback between the two strata. In the case of water pollution, for example, the receiving waterway has often been considered a free sink for the waste produced by a society, and its use in this manner has no effect on the operation of the social processes which control waste discharges. Therefore, the political, industrial, economic, and other structures which govern the input of wastes into the waterway need not be directly concerned with potential resources of the waterway. Control information from the management to the natural stratum is directed not toward maintaining production of goods from the natural stratum but rather to minimizing control inputs from the normative to the management strata in the form of adverse public opinion.

The role of the natural stratum is therefore quite different in analyses of pollution and exploitation ecosystems. In pollution ecosystems, the stratum serves to organize the behavior of the subsystems in response to inputs from higher strata; the natural stratum as a whole has mainly indicator value. In exploitation ecosystems, the processes on the natural stratum are directly linked to those on the managerial strata in a complex set of feedback loops, so that their treatment within a single analytical framework may be critical. In such a case, modeling and analytical considerations of different strata cannot be effectively decoupled from each other. The various elements considered in the analysis must all be compatible regardless of what stratum they lie on.

COMPATIBILITY BETWEEN DIFFERENT VIEWS OF A SINGLE SYSTEM

The notion of compatibility is conceptually simple, but operationally quite subtle. Basically, an analysis that considers various subsystems treats them in such a way that all can communicate with each other. After all, the subsystems do in fact communicate with one another in the real world. But the process of analysis requires simplifying assumptions which may make it rather difficult to achieve compatibility between various subsystems. Fortunately, the issue of compatibility relates only to communication between subsystems, and it sets constraints on their linkages rather than on the structure of individual subsystems themselves. Thus the notion of compatibility of subsystems resolves itself into that of consistency of information flow throughout the system.

Information Chains

This is not always a simple matter, as it includes not only the information passage between subsystems but also the time resolution within which that information must be interpreted. It is quite common, for example, for two subsystems to be linked with information which passes continuously from one to the other. The output of the first may be quite volatile, so that it varies greatly in short periods of time. But the input may be integrated by the receiving subsystem so that averages over relatively long periods are the stimulus for its precise response. This is typical of many predator-prey systems in which the predator is relatively long-lived and is characterized by a stable equilibrium population level (i.e. it is "K-adapted"; Wilson and Bossert, 1971) and the prey has a short life-span and a widely fluctuating population density (i.e. it is "r-adapted").

Information chains must also be complete. That is to say that if we view a simple system such as in Figure 4, we need to be especially careful to identify the information channels crossing between strata in both directions (Figure 4a). Control and monitoring information are linked through a series of subsystems within each stratum (Figure 4b). Finally, the network of information flows connecting the subsystems must be sufficiently complete that the control input and process outputs are connected in a realistic and technically feasible fashion (Figure 4c). In companion papers (Clapham and Pestel, 1978a, 1978b) the information chains needed to look at environmental problems of

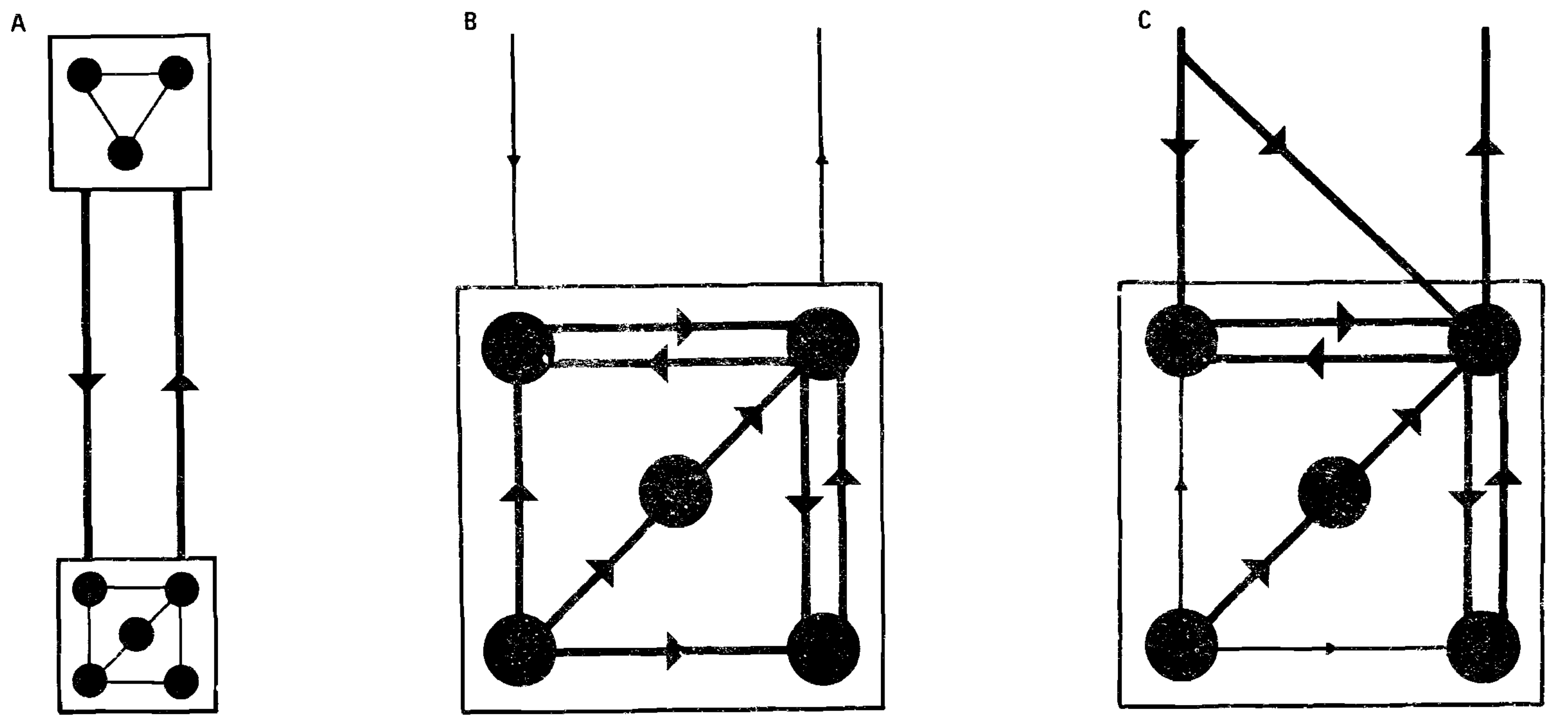

Figure 4. Schematic representation of the process of identifying complete information chains in multistratum systems.
a. identify the information channels crossing strata in both directions.
b. identify linkages among subsystems within strata.
c. complete chain so that intrastratal information flows are connected with control and monitoring information from other strata.

agricultural systems are specified, and the problems of completing the information chains and using them in policy analysis are discussed in detail.

But if information chains are to be complete, then each triplet of subsystem output-information-subsystem input (Figure 5) along the chain must consist of identities: the output of one system must be identical to the input of the next subsystem, and the set of all inputs and outputs is the information flow throughout the system. If this is not the case, either a translator must be built into the emitting or receiving subsystem (or perhaps into the communication channel itself), or the inconsistencies of the linkage render linkage dubious or impossible. This is obvious in principle, but it is often extremely unclear how to do it in the actual implementation of an analysis. For a model in which different subsystems are treated as different modules connected by information flows, it does not make any difference to the communication protocol what structure each module takes. But the requirement of identity of inputs and outputs for linked modules requires identity in units, time resolution and phasing, spatial resolution, and what might best be called the "character" of the variable.

These may or may not pose problems of specification. Units can always be adjusted through appropriate scaling or conversion factors which, within reasonable limits, will not introduce more than trivial round-off error into computation. But mismatches in temporal resolution or phasing may be much more problematic. When two interconnected modules have different time steps, there is always an implicit hierarchy of model structure within each module (Figure 6). In principle, either module may be treated with either time step. But there is a big difference between going from lower (i.e. finer) to higher (i.e. coarser) and vice versa. The former represents a concatenation of information, while the latter involves a disaggregation. It may not be a trivial exercise to concatenate information from one time step to another. But because all of the information is present, it

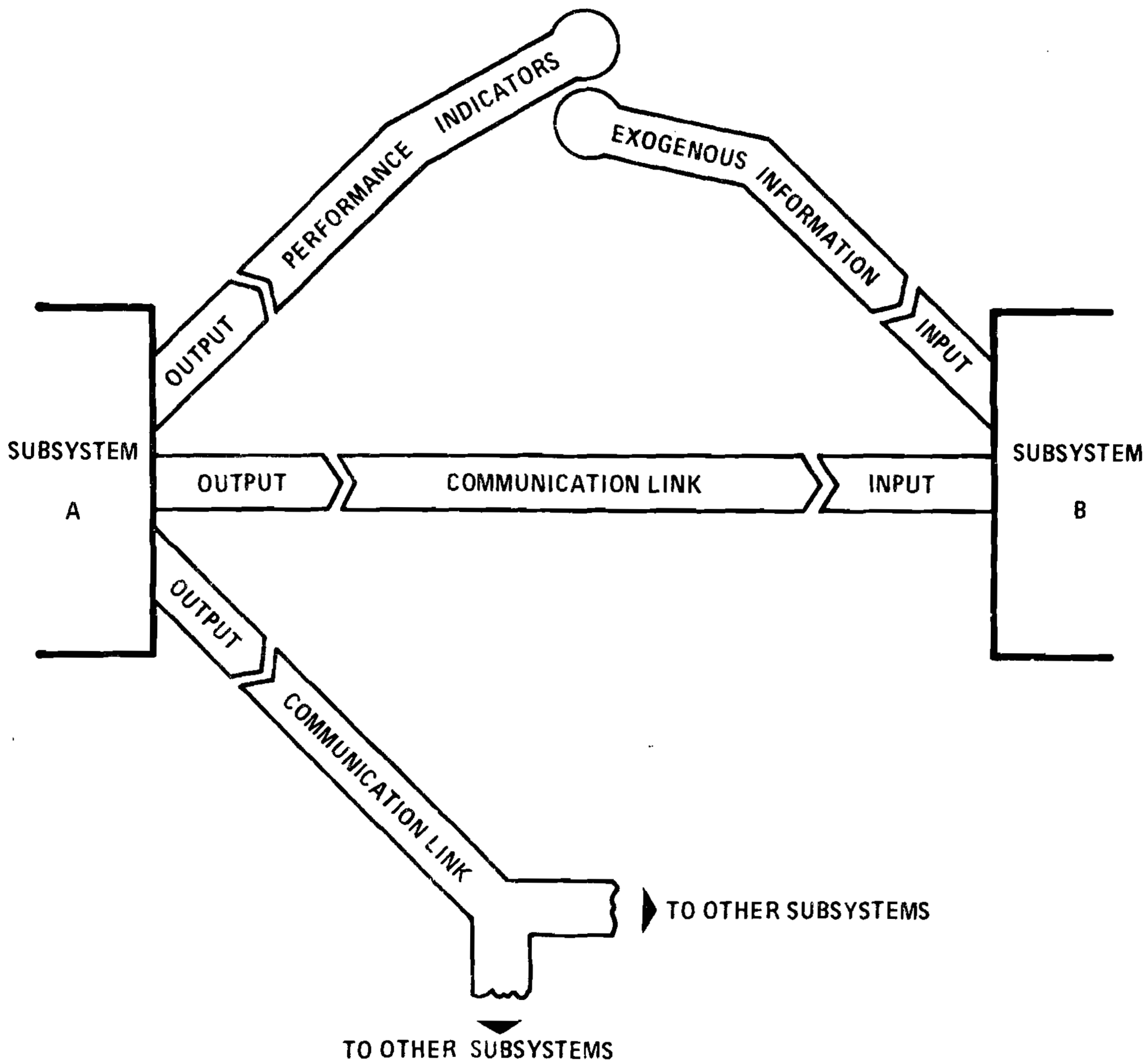

Figure 5. Schematic representation of the relationship between outputs and inputs of adjacent subsystems. Note that any one subsystem may communicate with several other subsystems, and that a single information channel may connect more than two subsystems.

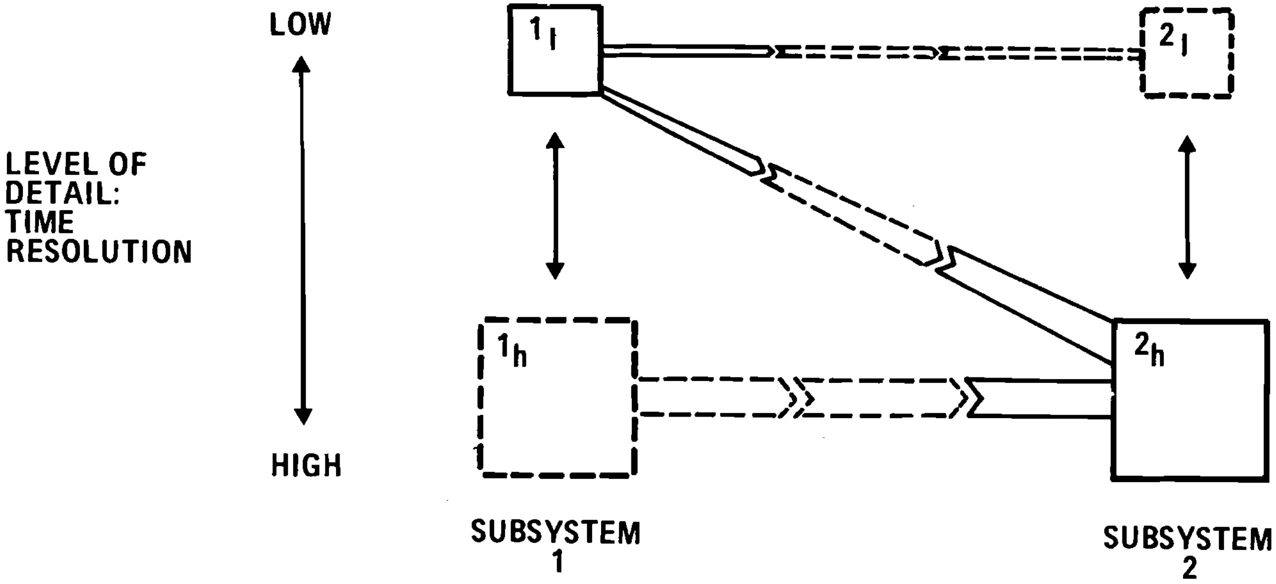

Figure 6. Schematic diagram of the mismatch between two subsystems, one of which (2_h) requires high time resolution of input, but the other (1_l) which can provide only a low time resolution of output into it. In principle, it is possible to construct a subsystem 1_h, which could provide information at the level of resolution required by existing subsystem 2_h, but it has not been done. Likewise, one could imagine a subsystem 2_l, which would be satisfied by the output of system 1_l. The pairs 1_h, 2_h, and 2_l, represent a hierarchy of representational detail within each subsystem.

is usually possible at least in principle. The disaggregative process of going from longer to shorter time steps is much more difficult, since the information content of the finer time step is greater. In principle, this requires that a sufficient structural basis be built into the model to generate the missing information. This is usually not feasible, since if the generation process could be modeled, it would probably be easier to model the basic process itself at the appropriate time scale.

Much more subtle, and often more important, is the matter of the "character" of a variable. One of the hardest problems of interdisciplinary research is that two closely related but different concepts may be given the same designation even though they are not, in fact, precisely the same. It is one thing to assert that the elements of the output-information-input triplet are identical, but it is not always obvious that the output of one subsystem really has the same connotation as the input to another (or more serious, that it does not). Precise definitions often get obscured when crossing from one discipline to another. This may not be a severe problem in very closely related subsystems where a single person is used to the problems of both even if he is more intimately acquainted with one than with the other. But it may be severe for cross-disciplinary modeling where people are not accustomed to dealing with the problems of all of the subsystems involved. For example, the "amount of irrigation water used" might seem to be a relatively straightforward concept. Indeed this would be a rather disaggregated and specific variable for an economic model and it might also be meaningful as the input for a crop-production subsystem model if changes in the mix of irrigation technologies used during the model run were consistent with those for the period of model parameter estimation. But for input to a model of soil-water balance, the precise mix of technologies (e.g. drip, spray, or trench) must be stated, as it makes a tremendous difference with regard to the evapo-transpiration and delivery of water to the root zone of the crop plant. Likewise, "pesticides" or "fertilizer" might seem to be relatively simple model variables. Given the data, empirical relationships could be constructed for which these inputs could be used quite effectively. But to study plant-soil-nutrient balances or synergistic-antagonistic pest-pesticide responses would require a much more detailed picture not only of the chemicals included at each point in the analysis but also of the application patterns and timing for the chemicals.

Just with the question of time-step, the notion of character of a variable implicitly includes the notion of model hierarchy. In the same way, it is often feasible to go from lower to higher on this hierarchy, although the step may be a relatively sophisticated one. But "character" is a much more inclusive concept than time-step. Few variables that pass between subsystems are constant in time, and the notion of timing may be important. If, as often happens, the timing is more important to one subsystem than to another, then the role of time (and hence the time-step question) needs to be considered explicitly, either on-line or in the process of parameter estimation. But character also includes the scope of definition of the variable. In the case of a complex variable (such as pesticide or fertilizer) it may be necessary to treat direct effects of each type in parallel as well as indirect effects such as synergism and antagonism.

Inherent Incompatibilities in Viewpoint

A related matter is the differences in viewpoints between the various disciplines involved in modeling different subsystems within a single analysis. In the extreme, we have distinguished between "economic" and "ecologic" approaches which, at least in their quantitative operational details, are very different. The "economic" view tends to be highly aggregated and empirical. It depends on numerical relationships based on phenomena upon which measurements can be made precisely and easily. The "ecologic" view, on the other hand, tends to be more disaggregated and structural. It attempts first to understand the structural relationships between elements and then estimate them in quantitative terms even when measurement is very difficult. The former emphasizes precision over realism (in the sense of Levins, 1966), while the reverse is true in the latter.

These differences are reasonable in the context of the subjects and approaches of the two sciences. But they often make it difficult for people of different backgrounds to cooperate with one another: the ecologist may distrust the more pronounced empiricism of the economist, and the economist may distrust the lower precision of the ecologist. The economist may ask that all concepts be reduced to some common indicator (such as money) before they can be considered; the ecologist may want to deal with things which cannot easily be reduced to a common indicator and which may not be quantifiable in principle. But even if the personal or professional difficulties are worked out, there may still be problems. Models tend to be disaggregated for those dimensions which are important for an analysis. Economic models, for example, tend to be disaggregated along factors like prices, commodities, and monetary flows. Ecologic models, on the other hand, tend to be disaggregated along factors like biological population stocks, energy flows, and materials transfers. Conversely, economic models tend to aggregate things like inputs to production processes and may even consider them all in terms of capital, labor, monetary terms, or so-called proxy variables which are not themselves the actual input to the process but which behave in a similar way. From the viewpoint of the economist, the use of such variables is warranted because they are often easier to measure or have a higher level of precision of measurement than a more physical kind of measure. The use of aggregate measures may embody some of the physical trade-offs which are possible within the system so that the ability of the model to track historical data is higher than it would be using detailed physical data. But the physical inputs which tend to be aggregated in an economic model are the most important inputs to an ecological model. This represents a mismatch between the approaches: the basic assumptions of the one (economic) cannot provide the fundamental information needed by the other (ecologic).

INTEGRATION OF COMPATIBLE MODELS

If ecologic and economic issues are to be approached in a single analysis--as they often must be--it is necessary to overcome the mismatch between the two approaches. This requires agreement on the goals of the linked model and development of a hybrid strategy within which the requirements of all constituent modules can be realized. This strategy must embrace the approaches to parameter specification and estimation as well as model structure and information passage throughout the model. The goals of the linked model must be directed toward specific uses--and also to specific users. The viewpoints needed for a linked modeling exercise must necessarily be wider than those of a disciplinary approach, and linking modules of different pedigree may require some relaxation of strongly held attitudes by both economist and ecologist in order to meet the expectations of potential users (who may or may not be actively involved in the linkage process). For example, the model must be both sufficiently precise (in the sense of Levins, 1966) to satisfy a user who is accustomed to economic models, and it must also be sufficiently structurally realistic to convince a user accustomed to ecological models that feedback processes are described adequately and correctly. This is an uncertain trade-off which is difficult to solve in practice. But a key requirement is that a linked model must convey insights to the user that he would not have gotten from a more customary economic or ecological model that did not consider the other strata. Even if he is aware of the deficiencies of the linked model (and all models have deficiencies of which the user should be aware), these insights compensate for them.

Integrated models are useful only when they clarify problems or improve perceptions relating to phenomena which cross strata within a single system. For this reason, the effectiveness of any given model can be measured by the degree of insight it provides into interstratal feedbacks and interactions. Its goals are therefore different from those which currently constitute the norm for economic and ecosystem studies. They span the range of model application, shown in Table 1. Examples of problems that might be investigated through a linked model for each of the applications are also indicated. All of these examples have one thing in common: the feedbacks across strata are so important that the insights gained through understanding them far outweigh the deficiencies introduced by linking models which are usually left separate.

There are many problems inherent in a complex enterprise such as interstratal modeling of human ecosystems. The potential benefit is also very high, as is its cost if organized poorly. As an enterprise it is still in its infancy and there are not yet many concrete examples of human ecosystems which have been modeled in this fashion. Modeling is an art as well as a science, and there are many opportunities for creative linking. Of course the precise way of building a given model cannot be specified in a general paper such as this one. But because of the "art" dimension to modeling and the mismatch problems inherent in linking two approaches as different as economics and ecology there is an inherent credibility problem in all interstratal models of human ecosystems. This problem must be addressed as with all modeling efforts and the credibility of a linked approach must be established through a well thought-out validation procedure adapted to the specific needs of the modeling approach.

In a broad sense, we can identify several kinds of validation, some as summarized in Table 2. All of these approaches are important for at least some types of modeling purposes, and all may contribute to the degree to which we trust any particular model. There is a trade-off among validation criteria. For example, if one model does not track a historical time series quite as well as another it may have other properties which render it preferable for policy analysis or projections. These would be pointed out by structural analysis and expert opinion. Table 3 suggests the roles of the types of validation presented in Table 2 for the various model applications shown in Table 1.

Table 1*. Applications for models, with examples.

Application	Example
Model is a learning device for benefit of modeler, mainly to point out deficiencies in knowledge or understanding and to learn about system.	Any aspect of human ecosystem where behavior or governing principles are not well understood: e.g., pest management.
To assist in organization of a data collection system; i.e. to determine the types, frequency, reliability, etc. of data.	Aspects of human ecosystems for which behavior and governing principles are well understood in a qualitative fashion, but for which detailed quantitative observation have not been carried out, e.g. effect of technology innovation and diffusion on farm production.
To understand structure and behavior and to organize and integrate knowledge into a common structural base (e.g. the ecosystem).	Most ecosystem-level models: e.g. International Biological Programme biome models for natural ecosystems, any descriptive ecosystem-level management model for human ecosystem.
Assessment of comparative statics and dynamics of models and model components: e.g., testing of *ceteris paribus* assumptions.	Policy-effectiveness or technology-assessment modeling of historical periods to gauge the impact of policy or technological change.
Assistance in policy design: Projection of alternative futures under different assumptions of policy implementation or patterns.	Practical elucidation of impact of environmental constraints on agriculture, long-term development of problems such as soil quality or erosion under policy constraints or alternative assumptions of environmental (e.g. climatic) change.

*Tables 1 and 2 are based largely on personal communication with Dr. Inderjit Singh; World Bank.

Table 2. Types of validation for models.

Validation Criterion	Method of Validation
Structural	Qualitative assessment of structural realism of the model and the constraints put on estimability of parameters by this structure. Assessment of the form of each relationship independent of and in consideration with other relationships. This sort of validation can be carried out before numerical results are obtained.
Quantitative analysis of results	Quantitative assessment of the output of a model by comparison with observations or time-series data. May have statistical measure of model performance or may be accepted "by eye".
Qualitative analysis of results	Qualitative assessment of levels and compositions of activities produced as results. This is usual in a validation of alternative futures and may be used in conjunction with a historical time series or a standard scenario.
By observation	Quantitative or qualitative comparison of results with actual measured data where measurement postdates the model run or data were not used in parameter estimation.
By expert opinion	Qualitative assessment of the realism of the model for dimensions beyond any of the above, based on experience and intuitive grasp of the probable response of the system for conditions beyond those that could be included in model specification and estimation.

Table 3. Validation techniques needed for different applications of models.

	Validation Techniques				
Applications	Structural	Quantitative Analysis of Results	Qualitative Analysis of Results	Observation	Expert Opinion
Learning Device	useful, but not required	not required	useful	probably not applicable	useful
Organizing and Collection system	useful, but not required	probably not applicable	useful	probably not applicable	useful
Structural and Behavioral Understanding	essential	very useful	essential, especially behavioral results	probably not applicable	essential
Organizing and Integrating Knowledge	essential	very useful	very useful	essential	essential
Assessment of Comparative Statics and Dynamics	essential	essential	essential	useful	useful
Assistance in Policy Design	essential	essential	essential	very useful	essential

The treatments of human ecosystems as multilevel hierarchical systems which can be modeled as a series of subsystems united by a consistent information passage is one way of looking at such systems. In this paper, we have concentrated on the problems and general aspects of this view. But if the view is to be useful, it must be implementable for a real system on a real computer. In subsequent papers of this series, we shall provide more concrete views as to how this can be done. We believe, however, that this approach is feasible and useful for deriving significant insights into important problems of society.

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